

INFLUENCE OF COOLING RATE DURING QUENCHING ON IMPACT TOUGHNESS OF A HOT-WORK TOOL STEEL AT AMBIENT TEMPERATURE AND AT 200 °C

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Resume

Gross cracking of die-casting dies with inferior toughness sometimes occurs through too low preheating temperature and/or too slow cooling during quenching. This study aimed to clarify the influence of cooling rate on the toughness of the hot-work tool steel grade Uddeholm Vidar Superior at ambient temperature and at 200 °C, a typical preheating temperature for aluminium die-casting dies. Toughness was measured through instrumented Charpy V-notch impact testing. The decrease in energy absorption with increasing cooling time between 800 °C and 500 °C at both ambient temperature and 200 °C was pronounced. At ambient temperature, the decrease in total energy was a consequence of a decrease in initiation energy whereas, at 200 °C, the decrease in total energy was due to a decrease in propagation energy. The present investigation does not explain the decrease in toughness with increasing cooling time between 800 °C and 500 °C. This can only be revealed by studying the metallographic structure by light microscope, scanning electron microscope, and transmission electron microscope.

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1. Introduction

Gross cracking of die-casting dies with inferior toughness sometimes occurs through too low preheating temperature and/or too slow cooling during quenching. In large die-casting dies it is difficult or even impossible to obtain sufficiently fast cooling *below* the surface, especially in the core, because the heat transfer to the quenching medium is limited by the heat conductivity of the steel. The importance of a sufficiently fast cooling during quenching is manifested in North Americas Die Casting Association's (NADCA's) criterion of a minimum cooling rate of 50 °F (28 °C) per minute [1] at a distance from the surface of 15,9 mm (0,625 inches). NADCA emphasizes that in dies with ruling sections exceeding about 300 mm (12 inches), it may not be possible to achieve this quench rate with all equipment. The difference in quench rate between the surface and the inner part of the die increases with

increasing cross-section and cooling capacity of the quenching medium. Table 1 illustrates the difference in cooling rate between surface and core of blocks of Uddeholm Orvar Supreme (X40CrMoV5-1) quenched in a vacuum furnace at different nitrogen gas overpressure. The table reveals that the cooling rate in the core of the two large sections was far from fulfilling the NADCA's minimum value. This means that it is difficult or even impossible to exceed the minimum cooling rate in the centre of large dies.

The influence of the cooling rate on the toughness of tool steels have been investigated earlier [2-6] but never by instrumented impact testing. The aim of this study was to clarify the influence of cooling rate on the toughness of Uddeholm Vidar Superior at ambient temperature and at 200 °C, which is a typical preheating temperature for aluminium die-casting dies. Toughness was measured through instrumented Charpy V-notch impact testing.

Table 1

Cooling time between 1025 °C and 540 °C of test blocks of Orvar Supreme (X40CrMoV5-1) quenched in vacuum furnace at different nitrogen gas overpressure (2). Length of blocks: 500 mm.

| Cross section | 3 bar overpressure | | 5 bar overpressure | | 10 bar overpressure | |
|-------------------|--------------------|-----------|--------------------|-----------|---------------------|-----------|
| | Surface | Core | Surface | Core | Surface | Core |
| 508x127 mm | 20 °C/min | 16 °C/min | 23 °C/min | 19 °C/min | 24 °C/min | 20 °C/min |
| 610x203 mm | 12 °C/min | 10 °C/min | 16 °C/min | 11 °C/min | 17 °C/min | 10 °C/min |
| 762x280 mm | 12 °C/min | 6 °C/min | 14 °C/min | 7 °C/min | 23 °C/min | 7 °C/min |

2 Experimental

The steel grade tested was Uddeholm Vidar Superior, which is an electro slag remelt hot-work tool steel grade. According to EN ISO 4957 [7], the closest equivalent to this grade is X37CrMoV5-1, although Vidar Superior has lower silicon content: the chemical composition is presented in Table 2.

The cross section of the tested bar was 1000x200 mm. Charpy V-notch impact specimens were cut, according to EN ISO 3785:2006 [8], from the original bar in such a way the direction normal to the crack plane was in the short transverse direction (Z) and the direction of crack growth was in the transverse direction (Y). This specimen type is designated Z-Y according to both EN ISO 3785-2006 [8] and ASTM E23-07 [9]. The specimen type was formerly designated S-T. Two series of

specimens were manufactured, one consisting of 72 specimens and the other consisting of 60 specimens. Table 1 displays the quench rate in the temperature range 1025 °C to 540 °C. In CCT diagrams the cooling time between 800 °C and 500 °C is usually given. In order to obtain a correlation between these values a dummy impact specimen with a thermocouple in the centre was heat treated in a Schmetz vacuum furnace. During quenching, the nitrogen gas overpressure and the velocity of the fan were changed to obtain different cooling rates. The result is given in Table 3. Note that the quench rate is the mean rate in the temperature range in question. The temperature during quenching is not a linear function of the time so the rate in the temperature range 1025 °C to 540 °C should be higher than the rate in the range 800 °C to 500 °C.

Table 2

Chemical composition of test material.

| %C | %Si | %Mn | %Cr | %Mo | %V |
|------|------|------|------|------|------|
| 0.36 | 0.19 | 0.30 | 5.09 | 1.29 | 0.44 |

Table 3

Results from heat treatment trials in a Schmetz vacuum furnace. Austenizing at 1025 °C, quenching at different nitrogen overpressure and fan velocity.

| | | | | | | |
|---|------|------|------|-----|-----|-----|
| Cooling rate between 800 °C and 500 °C (°C/min) | 7 | 14 | 20 | 33 | 74 | 621 |
| Time between 800 °C and 500 °C (s) | 2411 | 1266 | 899 | 551 | 243 | 29 |
| Cooling rate between 1025 °C and 540 °C (°C/min) | 10 | 20 | 29 | 40 | 96 | 746 |
| Time between 1025 °C and 540 °C (s) | 2993 | 1471 | 1010 | 734 | 303 | 39 |

Table 4

Heat treatment of Charpy V-notch specimens.

| Test temp. | $t_{800-500^{\circ}\text{C}}$ | Austenization temperature | Austenization time | Quenching | Tempering temperature and holding time | Hardness |
|------------------------|-------------------------------|---------------------------|--------------------|--------------|--|----------|
| Am-bient (20°C) | 60 s | 1000 °C | 30 min | Nitrogen gas | 600 °C 2+2 h | 45 HRC |
| | 110 s | 1000 °C | 30 min | Nitrogen gas | 600 °C 2+2 h | 45 HRC |
| | 270 s | 1000 °C | 30 min | Nitrogen gas | 600 °C 2+2 h | 45 HRC |
| | 370 s | 1000 °C | 30 min | Nitrogen gas | 600 °C 2+2 h | 46 HRC |
| | 540 s | 1000 °C | 30 min | Nitrogen gas | 600 °C 2+2 h | 46 HRC |
| | 1200 s | 1000 °C | 30 min | Nitrogen gas | 600 °C 2+2 h | 46 HRC |
| 200°C | 70 s | 1000 °C | 30 min | Nitrogen gas | 600 °C 2h +595 °C h | 47 HRC |
| | 90 s | 1000 °C | 30 min | Nitrogen gas | 600 °C 2h +595 °C h | 46 HRC |
| | 270 s | 1000 °C | 30 min | Nitrogen gas | 600 °C 2h +595 °C h | 47 HRC |
| | 400 s | 1000 °C | 30 min | Nitrogen gas | 600 °C 2h +595 °C h | 47 HRC |
| | 1400 s | 1000 °C | 30 min | Nitrogen gas | 600 °C 2+2 h + 595 °C 2 h | 47 HRC |

The Charpy V-notch specimens were heat treated in the same furnace as before. In each set of twelve specimens the dummy specimen with a thermocouple was included to determine cooling time between 800 °C and 500 °C: this was designated $t_{800-500^{\circ}\text{C}}$. The full heat treatment is presented in Table 4. The intention was to quench one set of specimens slower than the NADCA minimum rate, another set close to the minimum rate and the rest of the sets faster the minimum rate. The cooling rate could not be controlled exactly through setting the nitrogen gas overpressure and the velocity of the fan: it differed slightly between different runs. Consequently the desired cooling rates were not exactly obtained. The series intended for testing at ambient temperature and 200 °C were not heat treated on the same occasion. This explained why the cooling rates were not equal. In order to obtain equivalent hardness the tempering procedure were not equivalent for all series.

Testing was performed with a 150 J U-type impact testing machine from Roell Amsler in Ulm, Germany. An instrumented tup with a 2.2 mm radius was used and the European standard for instrumented impact testing

(EN ISO 14556-2000 [10]) was followed. Twelve specimens per cooling time and test temperature were tested.

Maximum force (F_m), general yield force (F_{gy}), total displacement (s), initiation energy, and propagation energy were determined by Roell Amsler's software TestExpert II. The results were plotted in Microsoft Excel and an equation, suggested by Wallin [11] (but without any fixed parameters), was used to fit a curve to the energy and displacement data points. In each series of twelve specimens, the fracture surface of the specimen closest to the mean value was investigated with scanning electron microscopy (FEI Quanta 600 Mark II).

3. Results

There was a considerable difference between ambient temperature (20°C) and 200 °C (Fig. 1):

- The energy absorption at 200 °C was considerable higher than energy absorption at ambient temperature in the whole cooling time range.

- The decrease in energy absorption at short cooling times was more pronounced at 200 °C than at ambient temperature.

- General yielding only occurred at the shortest cooling time at ambient temperature. At 200 °C, general yielding occurred at all cooling times.

- At 200 °C the maximum force did not decrease up to 400 s: at longer cooling times, there was a negligible decrease. The maximum force at ambient temperature for the shortest cooling time was equivalent to the corresponding value for 200 °C: the small difference was most likely caused by the

difference in hardness of 1-2 HRC. At ambient temperature and longer cooling times, the maximum force decreased step-wise.

- The displacement at ambient temperature decreased quickly between 60 s and 100 s: at longer cooling times the decrease was negligible (Fig. 2). At 200 °C, there was a fast decrease in total displacement up to 400 s. The appearance of the total displacement curve was similar to the total energy curve; this was expected as the maximum force changed very little.

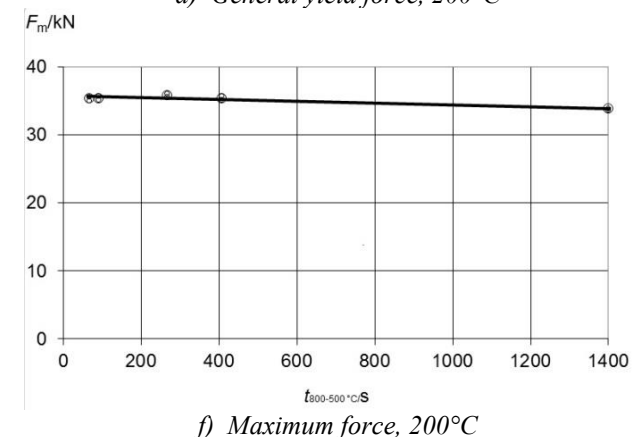
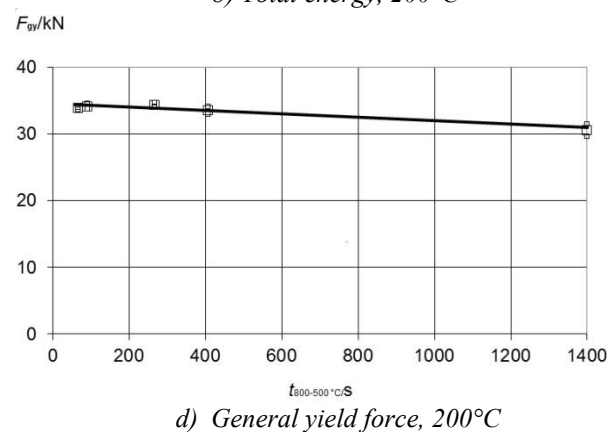
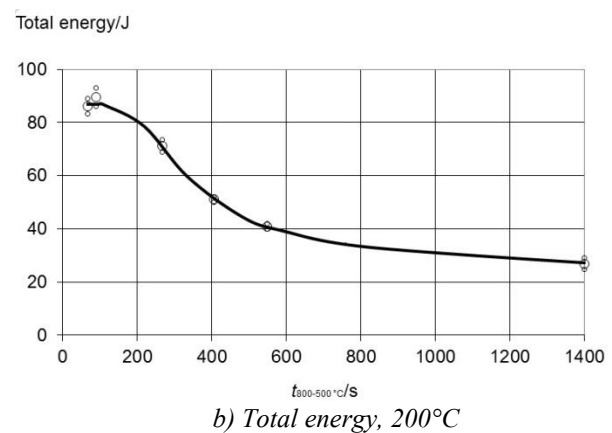
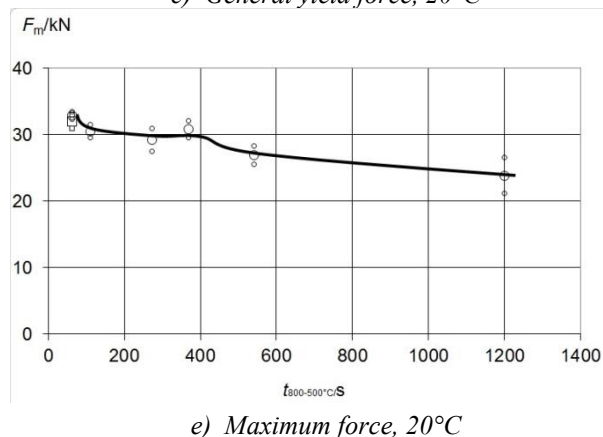
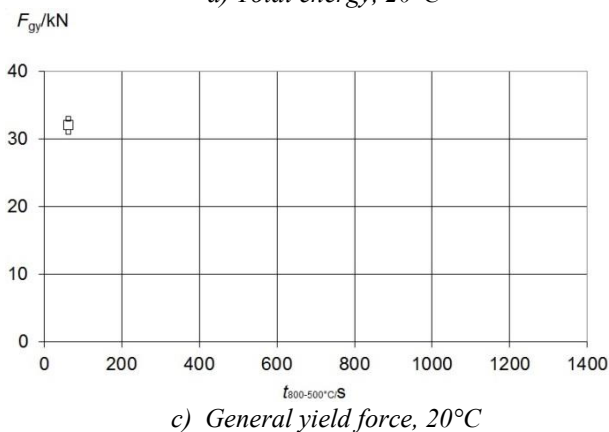
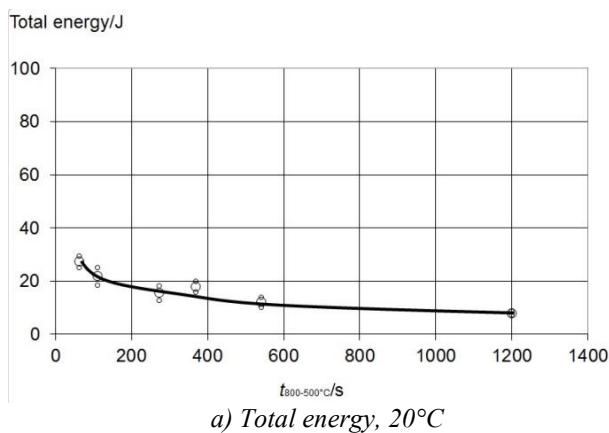


Fig. 1. Total energy absorption, general yield force and maximum force as a function of $t_{800-500}^{\circ}\text{C}$.

- The initiation energy was higher at 200 °C than at ambient temperature over the entire cooling time range; except for the shortest cooling time, where initiation energies were equal.

- The propagation energy at ambient temperature was small and almost independent of the cooling time. At 200 °C there was a pronounced decrease between 70 s and 400 s.

In the fastest cooled specimens tested at ambient temperature the fracture was initially

fibrous but changed to quasi cleavage after some tenths of a millimetre (Fig. 3). The fracture type of the specimens in the slower cooled series tested at ambient temperature were fully quasi cleavage.

The specimens with the shortest cooling time tested at 200 °C had fully fibrous fracture (Fig. 4). In the slower quenched specimens, fibrous fracture was dominant but some quasi-cleavage fractures were present.

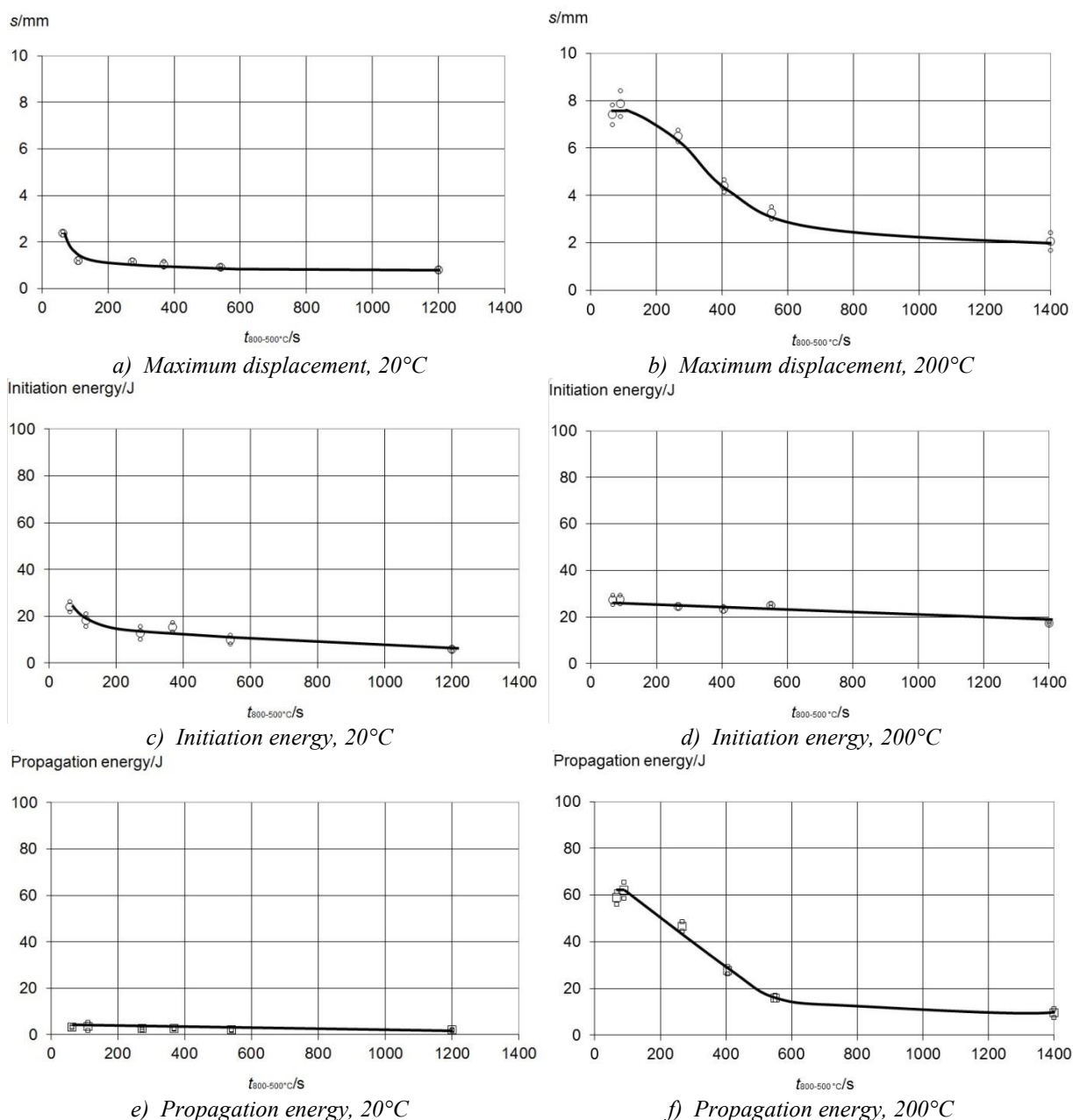


Fig. 2. Total displacement, initiation energy and propagation energy as a function of $t_{800-500\text{ °C}}$.

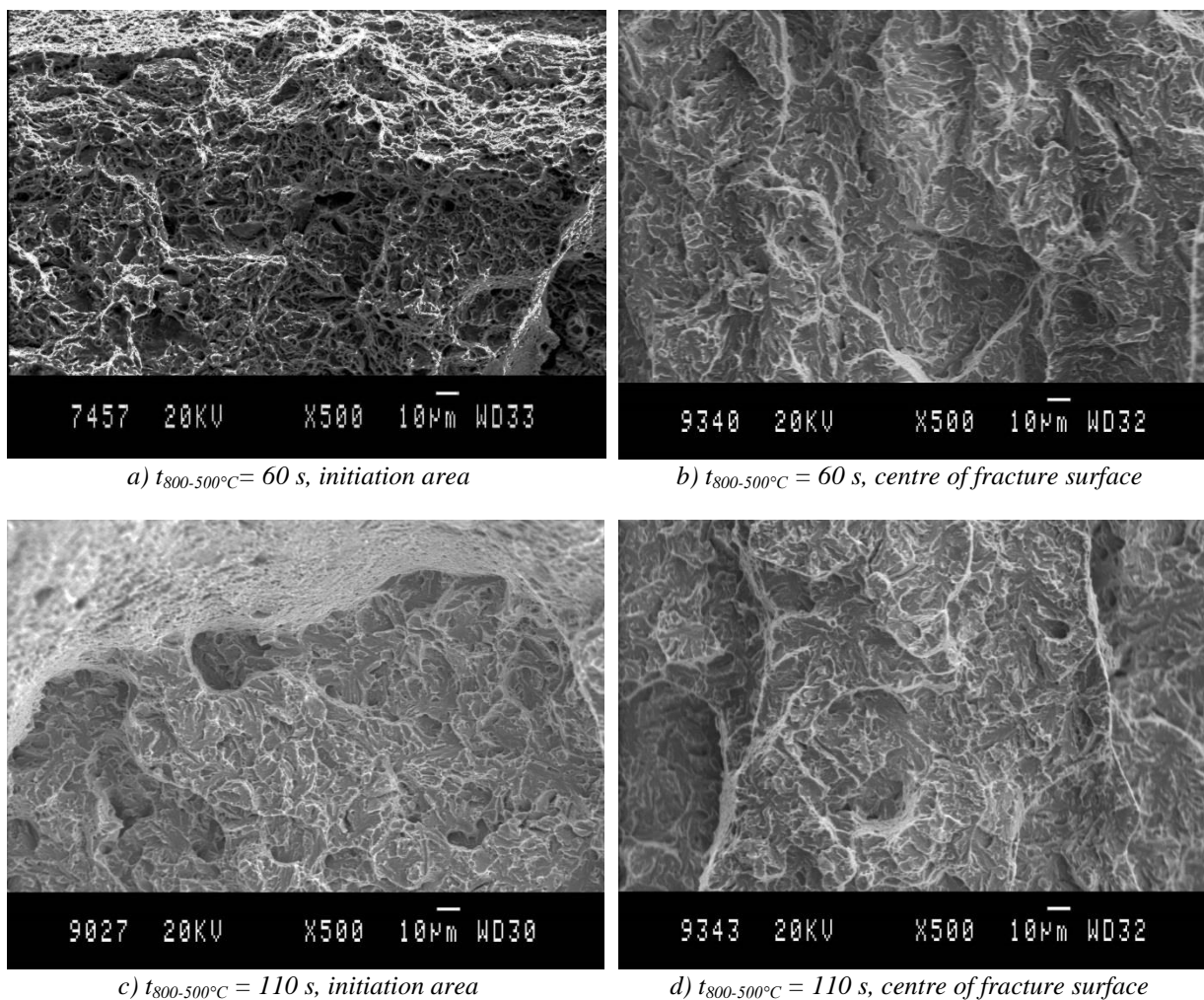


Fig. 3. Fracture appearance of specimens tested at ambient temperature. The fibrous zone was sheared off after the crack was initiated.

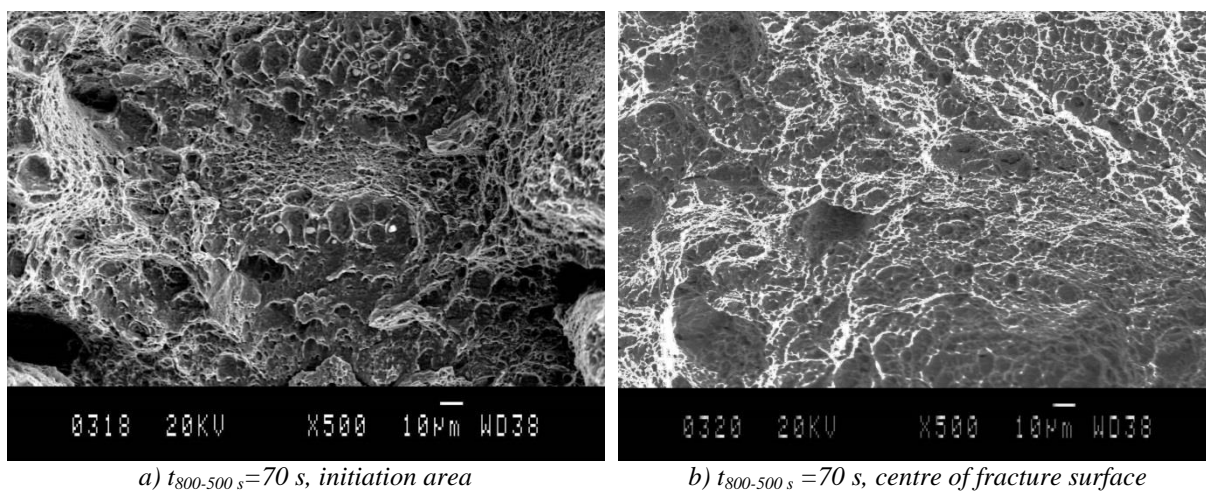
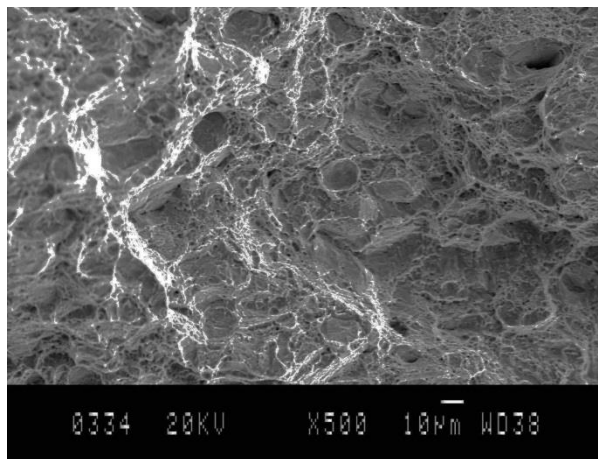
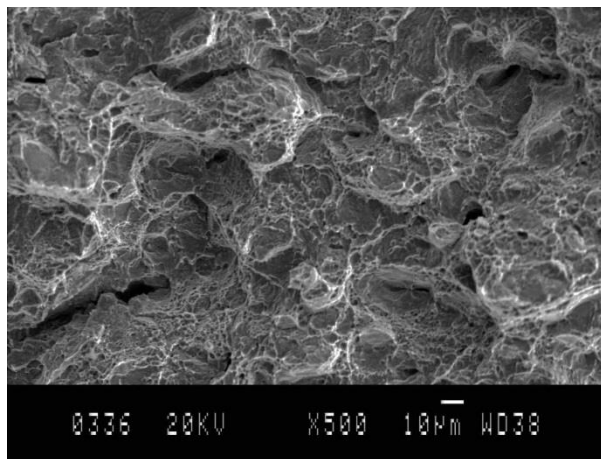
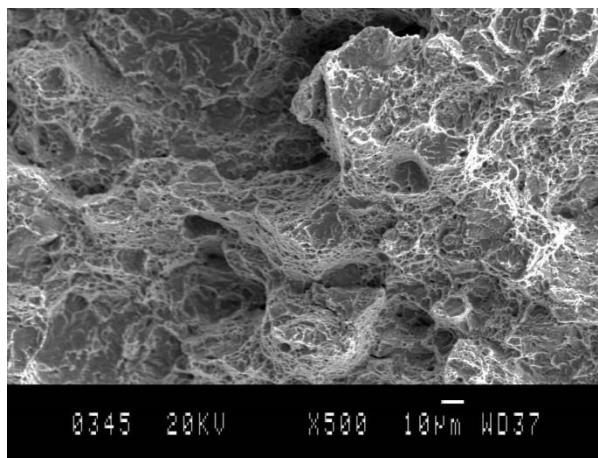
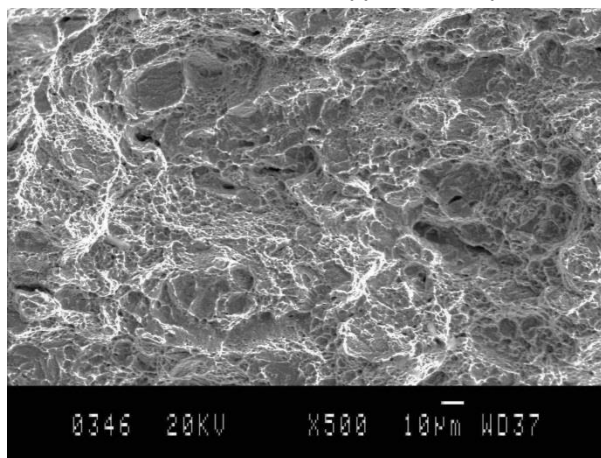


Fig. 4. Fracture appearance of specimens tested at 200 °C.

c) $t_{800-500\text{ s}}=400\text{ s}$, initiation aread) $t_{800-500\text{ s}}=400\text{ s}$, centre of fracture surfacee) $t_{800-500\text{ s}}=1400\text{ s}$, initiation areaf) $t_{800-500\text{ s}}=1400\text{ s}$, centre of fracture surface

continue of Fig. 4. Fracture appearance of specimens tested at 200 °C.

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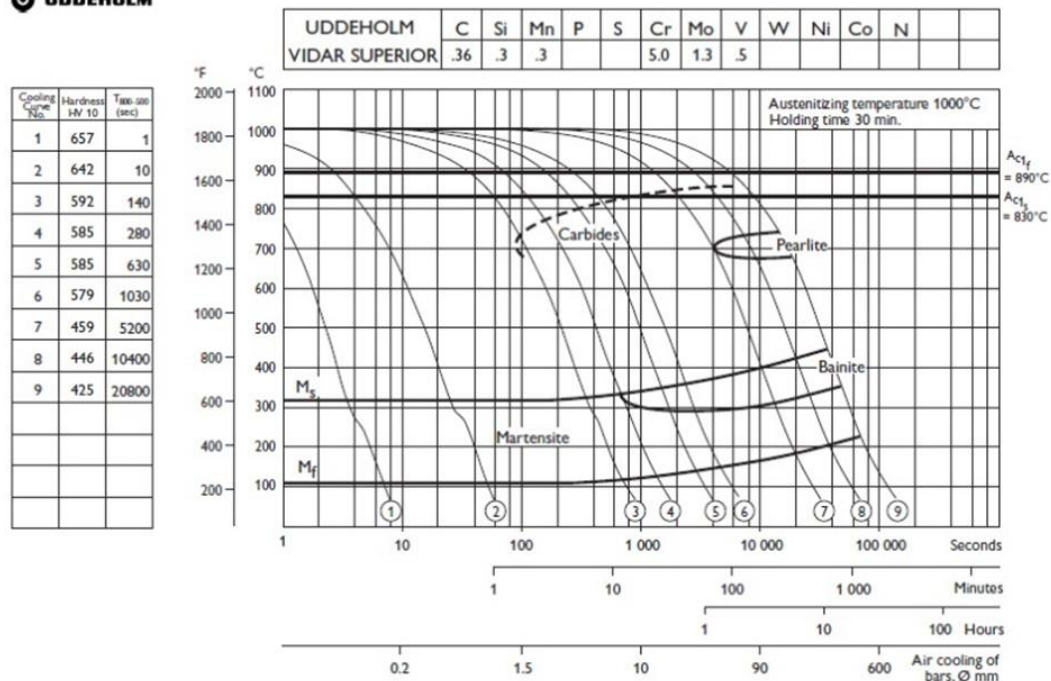


Fig. 5. CCT diagram of Uddeholm Vidar Superior.

4. Discussion

The decrease in total energy absorption with increasing cooling time at ambient temperature was a consequence of a decrease in initiation energy. The decrease between cooling times 60 s and 110 s presented itself in a change in fracture type in the initiation area from fibrous to quasi cleavage and in a decrease of the total displacement.

In all series tested at 200 °C, fibrous fractures were dominant in the initiation area of the specimens, and was the reason the initiation energy decreased slowly. The decrease in total energy was due to decrease in propagation energy, presented as a decrease in total displacement. The decrease in propagation energy and displacement did not produce an obvious change in fracture appearance. The decrease in energy absorption at short cooling times could not be explained by precipitation of carbides at grain boundaries, as no intergranular fractures were observed. Neither did the formation of bainite explain the influence of cooling time on energy absorption, as substantial amounts of bainite only form at cooling times exceeding 300 s (Fig. 5).

5. Conclusions

There was a pronounced decrease in energy absorption with increasing cooling time between 800°C and 500°C at both ambient temperature and 200 °C. At ambient temperature the decrease in total energy was a due to a decrease in initiation energy, whereas at 200 °C, the decrease in total energy was a consequence of a decrease in propagation energy. As aluminium die-casting dies are generally preheated at about 200 °C, it is relevant to measure toughness at this temperature when the influence of the cooling

rate during quenching on the toughness of steel intended for aluminium die-casting dies is an issue.

The decrease in energy absorption with increasing cooling time between 800 °C and 500 °C could not be explained from the CCT diagram and the change could only be partly explained by differences in the fracture appearance. A more thorough investigation of the fracture surfaces of the specimens tested at 200 °C may reveal a difference in fracture appearance but not why it differs. As the change in fracture appearance should be a consequence of a change in the metallographic structure, further study of the metallographic structure with light microscope, scanning electron microscope and transmission electron microscope is required.

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